EFFECTIVENESS OF A HIGH–PRESSURE WATER–FOGGING SYSTEM IN CONTROLLING DUST EMISSIONS AT GRAIN RECEIVING

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ABSTRACT. *Grain dust at the receiving area is a fire hazard, a health concern, and a sanitation problem and should be controlled. The effectiveness of a high–pressure water–fogging system in controlling grain dust emissions was evaluated with corn and wheat while spouting 2.1 m³ (60 bu) of grain into a test chamber. Dust/fog emissions and deposits along with entrained airflows were measured for four fog treatments, a control, and an air–blower treatment at each of two grain flow rates. The uncontrolled dust emissions varied with grain type and grain flow rate. Water–fog sprays, when applied across the top of the test chamber, redirected the airflow downstream of the spray nozzles and reduced dust emissions significantly. Dust reductions ranged from 60% to 84% for corn and from 35% to 73% for wheat. However, the sprays produced significant fog emissions and deposits in proportion to the liquid supply. At the highest spray rate (855 g/min), fog emission was 32 g/min (3.8%), and fog deposits ranged from 1.4 to 7.1 mg/cm²/min.*

Keywords. Airflow, Dust control, Dust deposits, Emissions, Fog, Grain dust, Spray.

rain dust clouds are generated whenever grain is mechanically conveyed, agitated, or processed. The resulting airborne dust concentrations are a nuisance and a potential respiratory risk for workers. High concentrations of dust in equipment provide fuel for a probable flash fire or dust explosion. The settled dust that layers in facilities can fuel a secondary dust explosion. The dust also provides food for insects that can infest stored grain.

Dust emissions are a function of air movement and the dustiness of the grain. Grain dust particles commonly range in size from less than 5 to over 100 μm (Martin, 1981). These particles have relatively low settling velocities in air, ranging from 0.001 to 0.25 m/s (Hinds, 1982), and are carried downstream by airflow. In a grain–receiving area, some airflow movement is generated as grain fills the hopper and displaces air from the hopper. Additional airflow is entrained with the grain stream while it falls into the receiving hopper; the amount of entrained air depends on grain drop height and flow rate (Cooper and Arnold, 1995).

Grain dustiness varies with grain type and condition. Corn is generally dustier than wheat. Using an alcohol rinse, Martin and Lai (1978) found that corn samples averaged 0.082%

residual rinsed dust, while wheat samples averaged 0.025%. Converse and Eckhoff (1989) observed that the amount of dust collected in a grain elevator's pneumatic system from corn dried with propane–heated air was more than twice that of corn that had been air dried with an aeration system.

Recent research has quantified dust emissions in grain–receiving areas. Kenkel and Noyes (1994) measured dust emissions at a grain–receiving area of a country grain elevator while receiving wheat. For a hopper–bottom semi–truck trailer, the average airborne dust emission was 9.5 g/tonne (0.019 lb/ton), and the average floor dust was 17 g/tonne (0.034 lb/ton). For an end–dump grain truck, the average airborne dust emission was 19.5 g/tonne (0.039 lb/ton), and floor dust was 24.5 g/tonne (0.049 lb/ton). Shaw et al. (1997) studied corn dust emissions at feed mill grain–receiving operations of cattle feedyards. Dust emissions during unloading of a hopper–bottom trailer averaged 8.5 g/tonne (0.017 lb/ton) with a standard deviation of 9.0 g/tonne (0.018 lb/ton). Based on published data, Midwest Research Institute (1998) has recommended total suspended particulate (TSP) emission factors at grain receiving of 17.5 g/tonne (0.035 lb/ton) for hopper–bottom trucks and 90 g/tonne (0.180 lbs/ton) for straight trucks.

Common dust control methods currently used by the grain industry are pneumatic systems for dust collection and oil additives for dust suppression. Pneumatic systems are generally effective in reducing dust at grain transfer points; however, they require high capital cost and large airflow rates, especially in areas with minimal confinement (Mains, 1998). Adding oil to grain is also effective in suppressing dust. Lai et al. (1984) showed that applying mineral oil at the elevator boot reduced the dust emissions by 90% at the elevator's gallery level. In addition, they observed that the oil treatment remained effective for several months. However, oil additives could reduce milling yields and increase sifter problems, as

reported by Reid (1987), and the FGIS maximum application rate of 200 ppm may be exceeded in multiple handlings.

Water sprays have been used for controlling dust in mines and on roads (Page, 1982; Jankowski et al., 1987; Ford et al., 1987; Page et al., 1994). In 1993, Environmental Engineering Concepts (Palm Springs, Cal.) marketed a water fogging system for grain dust control, claiming effective dust control with only 0.01% moisture addition to the grain stream (1 kg H_2O per 10,000 kg grain). Water fog systems could be an alternative dust control method. However, the effectiveness of such a system in controlling grain dust emissions has not been documented.

This research investigated the effectiveness of a water fogging system in controlling grain dust emissions for a grain–receiving application. The specific objectives were:

- Determine the potential reduction of grain dust emissions with spray–fog
- Determine airflow associated with the grain flow and spray–fog treatments
- Determine potential dust and fog deposits from spray–fog treatments.

MATERIALS AND METHODS

SPRAY SYSTEM

The spray system used in this study (model E1, Environmental Engineering Concepts, Palm Springs, Cal.) consisted of water filters, an electric motor, a pump, lines, pressure gauges, and nozzles. The nozzles had a 0.20 mm (0.008 in.) diameter orifice with internal impellers. The pump was attached to a city water line via a garden hose. For the test, the pump was operated from 5.5 MPa (800 psi) to over 8.3 MPa (1200 psi). The systems have been used mainly for localized cooling for outdoor businesses in arid climates, and in some cases, for dust control in mineral processing facilities.

Two randomly selected nozzles were tested at a commercial laboratory (Spraying Systems, Wheaton, Ill.) for measurement of droplet size distributions at 7.6 cm (3 in.) and 30.5 cm (12 in.) from the tip of the nozzle. The Spraying Systems laboratory used a phase–Doppler particle analyzer (PDPA). The volume median diameters (VMD) of the droplets were 12.5 and 21 µm at 7.6 cm and 30.5 cm, respectively, along the centerline of the nozzle with the nozzle pressure at 6.9 MPa (1000 psi). Particles were falling out of the plume after 30.5 cm, and most of those particles VMD ranged from 100 to 200 µm.

The average liquid flow rate for the nozzles listed by the manufacturer was 84 cm^3/min (0.02 gpm) at 5.5 MPa (800 psi). To determine uniformity among nozzles, a group of 36 nozzles were tested individually by collecting the spray into a graduated cylinder while timing with a stopwatch. The measured flow rates ranged from 76 to 104 cc/min. Sixteen nozzles, which had flow rates ranging from 79 to 88 cm^3/min, were then selected for this research.

Two spray lines were prepared from the selected 16 nozzles. The spray lines produced a plume of overlapping sprays (fig. 1) and induced airflow. Spray S1 used line 1, which had nine nozzles spaced 7.6 cm (3 in.) apart. Spray S2 used line 2, having seven nozzles were spaced 10.2 cm (4 in.) apart. For spray S3, line 1 was reduced to seven nozzles by inserting plugs for the outside nozzles. For spray S4, line 2 was reduced to five nozzles by inserting plugs for the outside nozzles. The
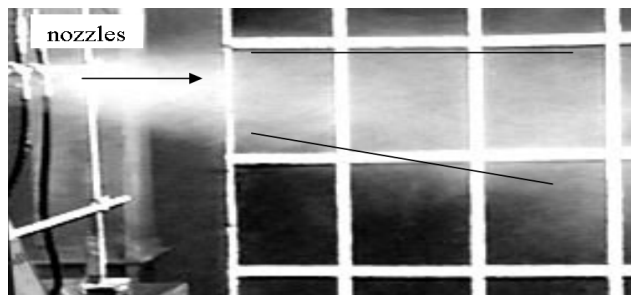

Figure 1. A line of fogging nozzles generating a plume of fine drops. The grid in the background has 30.5 cm (1 ft) spacing.

distance between the outside nozzles for spray treatments S1 and S2 was 61.0 cm (24 in.), leaving 7.6 cm (3 in.) spacing with the walls. For spray S3, the nozzles spanned 45.7 cm (18 in.), leaving 15.2 cm (6 in.) spacing with the walls. For spray S4, the nozzles spanned 40.6 cm (16 in.), leaving 17.8 cm (7 in.) spacing with the walls.

TEST CHAMBER

All tests were conducted using a test chamber that represented a narrow portion of a grain–receiving hopper. Typical grain–receiving hoppers hold from 17.6 to 35.2 m^3 (500 to 1000 bu) of grain, so that a truck can dump its complete load into the hopper at full flow in 2 to 5 min. The test chamber was 244 cm (8 ft) long, 76 cm (30 in.) wide, and 183 cm (6 ft) high (fig. 2). During the test, the chamber was filled to a grain peak height of 137 cm (54 in), equivalent to a volume of approximately 2.1 m^3 (60 bu) of grain. The top 30.5 cm (12 in.) of the chamber served as headspace for airflow and dust.

To facilitate airflow and dust emission measurements, the chamber was designed with three openings. The top had a 20×30 cm (8×12 in.) opening for the incoming grain chute. Each end had a 76×30 cm (30×12 in.) high opening for the inlet and outlet airflow. The spray lines were mounted at the inlet end, and sprays S1 to S4 were directed toward the outlet end. Airflow transitions were made at both ends for attaching a 25 cm (10 in.) diameter thin–walled tubing, which held propeller anemometers.
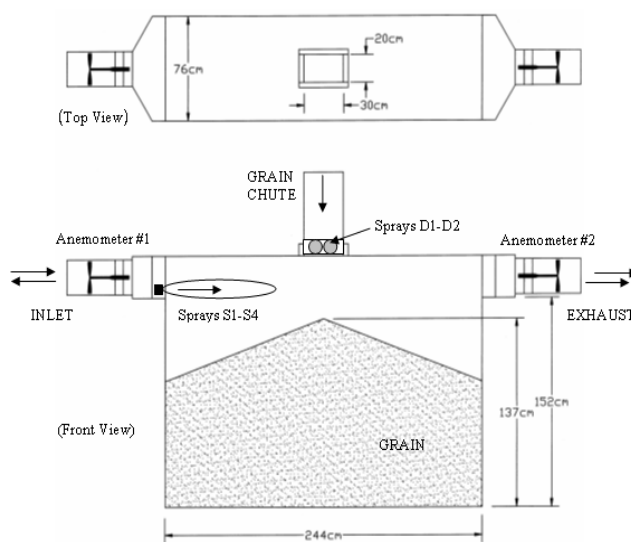

Figure 2. Top and front views of the experimental chamber and locations of spray treatments.

The test chamber was positioned in the truck bay of the grain–receiving area at the USDA–ARS concrete research grain elevator at Manhattan, Kansas. Grain was dropped from an overhead bin into the test chamber. After each test, the grain was emptied from the test chamber into the receiving pit. The doors of the receiving area were closed during testing to eliminate any effects of ambient wind.

EXPERIMENTAL PARAMETERS AND DESIGNS

Two series of tests were performed. The first series studied the effectiveness of spray–fog treatments when applied across the top of the test chamber, sprays S1 to S4 (fig. 2). The second series studied the effect of directly applying the spray–fog to the grain stream just prior to entering the test chamber, sprays D1–D2.

Test I: Spray–Fog Across the Top of the Receiving Hopper

The following factors were considered for the first series of tests: test treatment (6), grain lots (2), and grain flow rates (2) (table 1). The six test treatments included one control, one cross–flow of air from a blower, and four spray treatments (S1 to S4). The four spray–fog treatments provided a range of liquid flow rates and induced air intensities. There were 24 test combinations, each with three replicates, for a total of 72 trials.

As mentioned above, the spray induced airflow. The blower treatment was included to compare the effects of airflow (without fogging) and spray–fog treatments on dust emissions. For the blower treatment, a shaded pole blower (model 4C004, Grainger, Topeka, Kansas) was fitted on the end of a 25.4 × 61.0 cm (10 × 24 in.) long tube. This unit was mounted to the anemometer unit at the inlet end of the chamber. A baffle was added in the test chamber inlet to reduce the opening to 7.6 × 76.2 cm (3 × 30 in.) wide and to distribute the blower airflow uniformly to approximate the airflow induced by the nozzles.

Grain flow rate into the test chamber was controlled with the gate from the holding bin. When the gate was fully opened, grain flow rate was approximately 2.5 m³/min (72 bu/min). When the gate was partially opened, grain flow was approximately 1.7 m³/min (48 bu/min). These values were selected for the test chamber to be proportional to actual grain flow rates in full–scale hoppers. In a full–scale hopper, approximately 17.6 m³ (500 bu) of grain is dumped into the grain hopper in 2 min. As such, the grain flow rate would be approximately 8.8 m³/min (250 bu/min). Because the test chamber repre–

sented about 25% of the size of a full–sized hopper, the grain flow rate into the test chamber should be scaled by 25%, or to approximately 2.2 m³/min (62.2 bu/min).

The grain samples and grain flow rates were chosen to provide a range of dust and airflow conditions. The study used approximately 35 m³ (1,000 bu) of wheat and 35 m³ of corn. To determine the dustiness of each grain and the repeatability of dust emissions as produced by dropping the grain into the test chamber, pre–test drop trials were done. The pre–test trials consisted of 12 sequential 2.1 m³ (60 bu) drops at full grain flow with each grain. The pre–test corn dust emissions averaged 12.2 g/tonne with a standard deviation of 0.6 g/tonne. The pre–test wheat dust emissions averaged 4.2 g/tonne with a standard deviation of 1.4 g/tonne.

During the spray experiments, each 35 m³ grain lot provided twelve 2.1 m³ trials and provided one replication for all spray treatments for one grain sample and at two grain flows. The first 4.2 m³ (120 bu) of grain was emptied from the holding bin and used to purge the equipment. After the 12 drop trials, any remaining grain in the holding bin was emptied into the receiving hopper. The entire 35 m³ grain lot was cycled through the bucket elevator and concrete storage facility as a unit because the amount of grain damage and dust would be affected by the number of elevated cycles through a facility (Converse and Eckhoff, 1989).

The grain lots were sampled with an automatic sample diverter, while the 35 m³ (1,000 bu) batch was cycled into the holding bin. Each grain lot was sampled and graded three times. For both the wheat and corn, visual inspection and grain odor indicated no obvious mold growth. The average moisture, test weight, and dockage of the wheat were 13.0%, 61.8 lb/bu, and 1.7%, respectively. The wheat samples met U.S. Grade No. 1 standards. The average moisture, test weight, and broken corn and foreign materials (bcfm) of the corn were 11.2%, 58.6 lbs/bu, and 6.1%, respectively. The corn had higher than normal fine material, causing it to grade as U.S. Grade No. 5. The corn and wheat lots provided two distinct levels of dust emission and were not selected to compare wheat and corn.

Test II: Spray–Fog Directed on the Incoming Grain

For testing of direct application of spray–fog onto the grain, the spray configuration was varied and included one cross–flow spray (S2), two direct applications (D1 and D2), and a control (no spray). The cross–flow spray treatment was similar to treatment S2 in test I; it used seven nozzles at 6.9 MPa (1000 psi). Direct method D1 used four nozzles, while D2 used six nozzles at 6.9 MPa (1000 psi). An equal number of nozzles was positioned on each side of the grain chute, 15 cm (6 in.) above the test chamber and directed through two 12 × 30 cm openings (fig. 2). The four test combinations and four replicates yielded 16 trials for this series. Corn was used at full grain flow.

MEASUREMENT METHODS

The experimental dependent variables were dust emissions, fog emissions, dust deposits, fog deposits, and volumetric airflow rates. The emissions were collected with high–volume air samplers (PN 3–115–10, Environmental Process Instruments Division, Bendix Corp.). The air–sampling inlet had an opening of 6.4 × 20.3 cm (2.5 × 8 in.). The sampler was positioned next to the exit of the anemometer tube

Table 1. Experimental parameters and variables for study of the effectiveness of a fogging system to control grain dust.

Grain Samples	
	Wheat (U.S. Grade No. 1)
	Corn (U.S. Grade No. 5)
Grain Flow Rates	
	2.5 m³/min (72 bu/min)
	1.7 m³/min (48 bu/min)
Test Treatments[a]	
	C = Control
	blw = Blower
	S1 = 9n at 6.9 MPa (1000 psi)
	S2 = 7n at 6.9 MPa (1000 psi)
	S3 = 7n at 5.5 MPa (800 psi)
	S4 = 5n at 5.5 MPa (800 psi)

[a] In spray treatments S1 to S4, the number of nozzles (n) and nozzle pressure varied. The treatments were replicated three times for each grain and grain flow for a total of 72 trials.
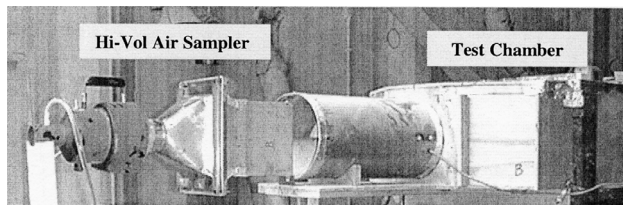
Figure 3. High–volume air sampler at the inlet of the test chamber.

(fig. 3). Because the air sampling area represented 25% of the anemometer outlet area, the air sampler was adjusted to maintain a flow rate near 25% of the exiting airflow rate.

The air filters were Type A/E, 20.3 × 25.4 cm (8 × 10 in.) glass–fiber filters (Pall–Gelman Sciences, Ann Arbor, Mich.). The filters were weighed before and immediately after each trial to determine the filter's wet weight. The filters were placed on trays and stored in racks while dried at 25°C and 60% RH for at least 24 h, and then re–weighed to determine dry weight. The difference between the wet weight and the dry weight represented the fog emissions. The difference between the dry weight and the pre–weight represented the weight of the collected dust. These filters were weighed on an electronic balance that was accurate to 1 mg (model PC180, Mettler Instruments, Columbus, Ohio).

Dust and fog deposition samples were collected after each trial from six locations in the chamber. The samples were collected using filters located on the test chamber walls and above the grain pile. Figure 4 is a schematic of filter locations at the outlet end. A similar group of filters was positioned at the inlet end. These filters (model PA41, Pall–Gelman, Ann Arbor, Mich.) were 12.7 cm (5 in.) in diameter. They were placed into filter holders, which were needed for handling and positioning the filters on the vertical surfaces. The holders had a 11.4 cm (4.5 in.) diameter opening, thus exposing an area of 102 cm^2 (15.9 in^2). The deposition filters were handled and analyzed following the procedure above but using an electron–
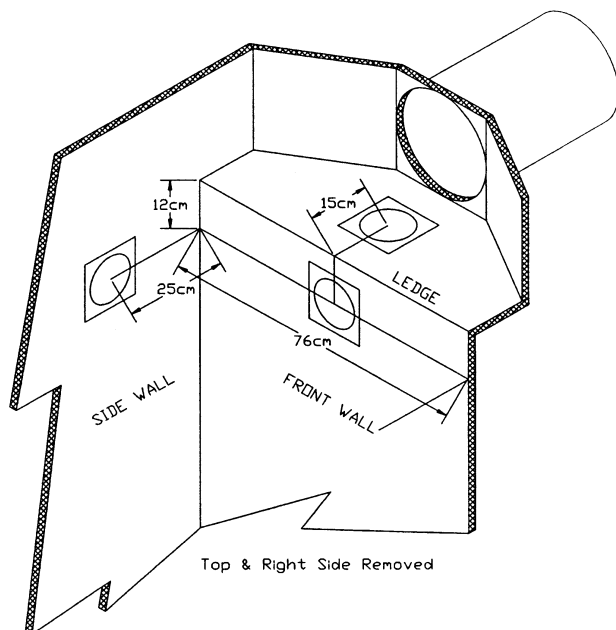

Figure 4. Positions of deposition sampling filters at the outlet end of the experimental chamber.

ic balance that was accurate to 0.1 mg (model 40SM–200A, Precisa Balance, Dietikon, Switzerland).

For each test, the following procedures were followed:
- The high–volume air samplers and the spray system were turned on about 5 s before the grain flow was started. Several seconds were required for the spray lines to become fully charged and functioning.
- The grain was dropped into the test chamber at the prescribed flow rate.
- The sprayer was turned off immediately after the grain flow had stopped. The high–volume air samplers were operated for an additional 5 s to account for the delayed response of the airflow and emissions after the grain flow was stopped.
- The emission sample filters and the deposition sample filters were weighed and set out to dry.
- The test chamber was emptied into the receiving hopper and prepared for the next test.

Airflow was measured during each trial with two propeller anemometers, one mounted at each end of the test chamber. The anemometers had a 22 cm (8.7 in.) diameter propeller (model 27106, R.M.Young Co., Traverse City, Mich.). They were mounted to a bracket inside of 25 cm (10 in.) diameter tubes. The anemometers were pre–calibrated using a wind tunnel, which was designed in accordance with AMCA standard 210–85 (AMCA, 1985). The anemometer voltage signals were recorded with a computer data acquisition system.

The time required to drop 2.1 m^3 (60 bu) of grain into the test chamber varied with gate opening and grain type. When the gate was fully opened, both wheat and corn were dropped in 48 to 52 s with an average of 50 s, and full grain flow was approximated as 2.5 m^3/min. When the gate was partially opened, the wheat was delivered in 68 to 72 s, while the corn was delivered in 78 to 82 s. Partial grain flow was approximated as 1.7 m^3/min using 2.1 m^3 and an average time of 75 s. The drop times were recorded with a stopwatch during each trial.

DATA ANALYSIS

The effect of spray treatment on dust emission for each grain type and grain flow rate was determined using the PROC MIXED technique in PC–SAS (version 8.02, SAS Institute, Cary, N.C.) with a 5% level of significance. PROC MIXED is an ANOVA procedure used with split–plot experiments. The LSMEANS (least square means) method was used to determine statistical significance of differences among treatment dust emission means.

The effectiveness of the spray treatment was determined by calculating the percent reduction in dust emission, that is:

$$\% \text{ reduction} = 100\% - 100 \times \frac{\text{avg.(treatment)}}{\text{avg.(control)}} \quad (1)$$

The variance for the ratio of means, $\dfrac{\text{avg.(treatment)}}{\text{avg.(control)}}$, was determined as outlined by Casella and Berger (1990). This variance is a function of the treatment standard deviation, the treatment mean, the control standard deviation, and the control mean. The variance was transformed to a standard error by taking its square root.

RESULTS AND DISCUSSION

AIRFLOW RATES FROM GRAIN AND SPRAY–FOG

The movement of dust particles depends on air movement because of the low settling velocities for small dust particles. Air was displaced from the test chamber as grain was dropped into the chamber. Airflow was also induced by the spray–fog treatments. Figure 5 shows the average exhaust airflow rates from the test chamber during the corn trials with full grain flow. For the control, the air was exhausted from each end of the hopper enclosure at approximately 1.4 m³/min (50 cfm). The sum of the exhausting airflow rates from both ends was 2.8 m³/min (100 cfm) and represents the air displaced by the grain plus entrained air in the grain stream. For spray treatment S1, air was exhausted at the outlet at 4.0 m³/min (140 cfm) and entered the inlet at 1.2 m³/min (42 cfm), with a net airflow displaced by the grain of 2.8 m³/min (100 cfm). The spray–fog treatments provided a curtain of airflow over the test chamber. In addition, some air recirculated within the lower chamber and back towards the nozzles.

EMISSIONS

The dust emissions from the control trials averaged 12 and 23 g/tonne for corn flowing at full and partial grain flow, respectively (fig. 6), and they averaged 5.0 and 5.7 g/tonne for wheat at full and partial grain flow, respectively (fig. 7). The difference in dust emission between the full and partial grain flow rates could be due to the shorter handling time for the full grain flow rate (approximately 50 s) compared to the partial grain flow rate (75 s). Dust emissions can be factored into time of emissions and rate of emissions. The rate of emissions varied with grain lot and was greater when handling corn. The range of dust emitted during the control trials was 5 to 23 g/tonne. As cited earlier, previous researchers (Kenkel and Noyes, 1994; Shaw et al., 1997) found average airborne dust emissions ranging from 9.5 to 19.5 g/tonne.

Test I: Spray–Fog Across the Top of the Receiving Hopper

Dust and fog emissions varied with spray treatment, grain sample, and grain flow rate. During spray treatments, emissions contained both dust and fog. Air and dust were exhausted through the inlet and exhaust openings of the chamber for treatment S4 and control. However, for the other spray treatments, the air and emissions were exhausted only from the outlet end (fig. 5) because the induced airflow from the spray process had greater inertia and mass flow than the air displaced by the grain.

Control and blower trial emissions results were not significantly different (figs. 6 and 7), thus the cross airflow from the blower did not reduce dust emission. The spray treatments significantly reduced dust emissions (figs. 6 and 7, table 2). Reductions were calculated as a ratio of the treated sample versus the control sample, as described in the data analysis section. The reductions varied with the grain sample and spray treatment. Reductions were higher for the corn sample, with its greater dustiness, than for wheat.

In general, the dust emissions from spray–fog treatments S1, S2, and S3 were not statistically different from each other (P > 0.05) but were all significantly lower than that from treatment S4. Spray treatments S1, S2, and S3 reduced dust emission by 75% to 84% for the dusty corn sample and by 63% to 72% for the clean wheat sample. Spray treatment S2 used seven nozzles spaced across the 76 cm opening and operated a 6.9 MPa. Spray treatment S4 used only five nozzles spaced
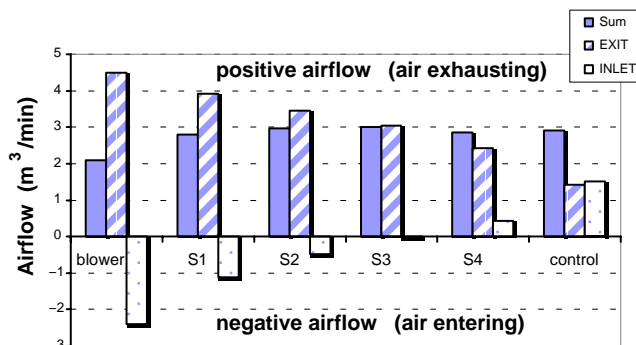

Figure 5. Average inlet and outlet airflow measurements and their summation for corn trials at full grain flow. Spray treatments S1 to S4 are outlined in table 1.
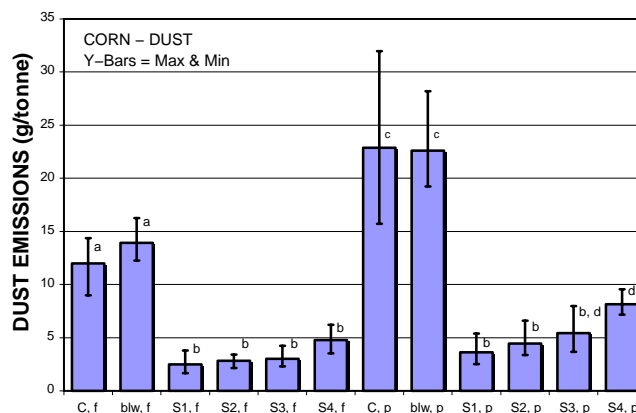

Figure 6. Average, maximum, and minimum dust emissions data for corn at full (f) and partial (p) grain flow. Means with common letter are not significantly different (P > 0.05). Spray treatments S1 to S4 are outlined in table 1.
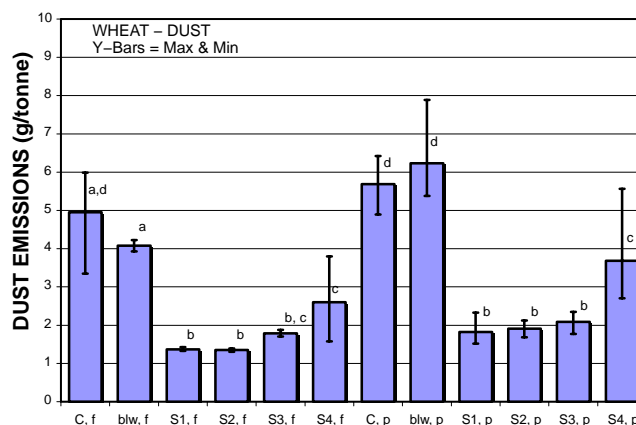

Figure 7. Average, maximum, and minimum dust emissions for wheat at full (f) and partial (p) grain flows. Means with common letter are not significantly different (P > 0.05). Spray treatments S1 to S4 are outlined in table 1.

across the 76 cm opening and operated at 5.5 MPa. Spray treatment S4 reduced dust emissions by 60% to 64% for corn and by only 35% to 47% for wheat. It appears that spray treatment S4 was not sufficient to dominate the airflow from the grain and force the flow uniformly across the top of the chamber. In addition, the drop flux from S4 was less than those for the other treatments, and the chance for drop/particle interaction was less.

Table 2. Dust emission reductions for spray–fog treatments, grain, and grain flow.[a]

| | Corn: Full Flow | | Corn: Partial Flow | |
| | $1 - \dfrac{\text{treatment}}{\text{control}}$ | SE | $1 - \dfrac{\text{treatment}}{\text{control}}$ | SE |
Treatment	(%)	(%)	(%)	(%)
S1	79	11	84	9
S2	76	8	81	11
S3	75	11	76	13
S4	60	15	64	14
	Wheat: Full Flow		Wheat: Partial Flow	
	$1 - \dfrac{\text{treatment}}{\text{control}}$	SE	$1 - \dfrac{\text{treatment}}{\text{control}}$	SE
Treatment	(%)	(%)	(%)	(%)
S1	72	8	68	9
S2	73	8	66	6
S3	64	10	63	7
S4	47	27	35	30

[a] Spray treatments S1 to S4 are outlined in table 1. Standard error (SE) was based on three samples.

Table 3. Spray–fog liquid flow rate and fog emissions.[a]

| | Supply | Emissions | |
Treatment	(g/min)	g/min	%
S1	855	32	3.8
S2	665	24	3.7
S3	588	16	2.7
S4	420	9	2.2

[a] Spray treatments S1 to S4 are outlined in table 1.

The fog emissions varied with spray treatments and ranged from 2.2% to 3.8% of the liquid supply (table 3). The liquid supply was calculated by multiplying the number of nozzles by the approximate flow per nozzle. At 5.5 MPa (800 psi) and 6.9 MPa (1000 psi), the manufacturer's literature–rated flows were 84 and 95 g/min/nozzle, respectively.

Test II: Spray–Fog Directed on the Incoming Grain

Table 4 summarizes the dust and fog emissions for the control, cross–flow (S2), and direct–spray configurations (D1 and D2). Dust emissions for the control in this series averaged 17 g/tonne. S2 reduced dust emissions to 4 g/tonne (76% reduction), while D1 and D2 increased dust emissions to 23 g/tonne. It appears that the small amount of water directly applied to the grain had no benefit in reducing the grain dust and that the air generated by the spray and entrained in the grain stream enhanced dust emissions. In addition, similar to the control, dust was emitted from both ends of the test chamber with sprays D1 and D2; with spray S2, on the other hand, dust was emitted only from one end.

DEPOSITS ON LEDGES AND WALLS

Deposits were collected on exposed surfaces above the grain and represented the maximum deposits for that location. Deposits on the grain were mixed in as more grain entered the test chamber. The grain pile also scoured the deposits off the walls when the test chamber was emptied. A thin layer of dust deposits was collected on the side wall and front wall during each drop trial. For the corn trials, the dust deposits ranged from 0.01 to 0.04 mg/cm^2/min. The dust deposits were highest on the ledges and ranged from 0.15 to 1.25 mg/cm^2/min

Table 4. Dust and mist emissions for test II: spray–fog directed on the incoming grain stream.[a]

| | Dust (g/tonne) | | Water (g/tonne) | |
Treatment	Avg.	Std. Dev.	Avg.	Std. Dev.
C	17.0	3.1	0.1	0.2
S2	4.0	1.1	12.4	1.2
D1	22.6	2.6	0.4	0.2
D2	23.1	4.2	0.8	0.4

[a] Treatments C and S2 are outlined in table 1. Treatments D1 and D2 were sprays applied directly to the grain. Standard deviation was based on four samples.

Table 5. Dust deposits (mg/cm^2/min^1) on inlet and outlet ledges for corn at full grain flow (2.5 m^3/min).[a]

| | Inlet | | Outlet | |
Treatment	Avg.	Std. Dev.	Avg.	Std. Dev.
C	0.87	0.12	0.95	0.12
blw	0.15	0.03	1.25	0.16
S1	0.38	0.11	0.70	0.16
S2	1.06	0.27	0.80	0.13
S3	0.30	0.06	0.55	0.15
S4	0.82	0.19	0.63	0.08

[a] Treatments C, blw, and S1 to S4 are outlined in table 1. Standard deviation was based on three samples.

Table 6. Fog deposits (mg/cm^2/min) at exit ledge, front wall, and side wall for corn at full grain flow (2.5 m^3/min).[a]

| | Ledge | | Front | | Side | |
Trt.	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
S1	7.14	0.75	3.72	1.36	1.44	0.41
S2	5.28	0.59	1.50	0.36	1.19	0.19
S3	2.34	0.25	0.59	0.15	0.54	0.19
S4	2.03	0.10	0.51	0.16	0.48	0.08

[a] Spray treatments S1 to S4 are outlined in table 1. Standard deviation was based on three samples.

(table 5). For the control trials, the amount of deposits at the inlet was close to that at the outlet. For the blower, S1, and S3, the deposits at the inlet were smaller to those at the outlet. For S2 and S4, the deposits at the inlet were greater than those at the outlet. The greater amount of deposits for S2 and S4 at the inlet could be due to the wider nozzle spacing at the side wall, which may have allowed some back–swirling of airflow and dust.

Table 6 shows the average fog deposition rates at the outlet ledge, front wall, and side wall for the spray treatments. The spray treatments deposited a thin layer of moisture on the exposed surfaces. The fog deposition rate varied with the spray treatment and sampling location. The deposition rate for spray S1 was 7.1 mg/cm^2/min at the ledge and 3.7 mg/cm^2/min on the front wall. In many environments, these surfaces would dry with time or would be rubbed off with grain handling. However, a user should be cautious and ensure that long–term problems, such as rusting, do not develop. The approximate exposed surface area for the ledge in the test chamber was 2300 cm^2 (2.5 × 1 ft). For the front wall of the test chamber, the exposed surface was approximately 7000 cm^2 (2.5 × 3 ft). The fog deposits for the ledge and front wall were approximately 19 g and 35 g, respectively, during the partial grain flow trials. These deposits were roughly 1.5% and 3% of the supply.

The spray fog system could be used in country elevators, terminal elevators, and feed mills that receive dry grain products, such as wheat, corn, or milo, during harvest. Receiving grain from producers using end–dump trucks is a dusty job. A short interval of fogging in the grain hopper would offer some relief.

One potential concern with the spray fog system is addition of water to the grain; it is unlawful to add water to merchandised grain for the purpose of adding weight (Federal Register, 1994). If all the water from a spray treatment having seven nozzles at 6.9 MPa was incorporated with grain flowing at 1.7 m^3/min, then only 0.95 kg of water would be added to 1500 kg of grain, and the grain moisture content would increase by approximately 0.06%. However, the actual moisture addition would be less because some of the spray fog would be exhausted, some would evaporate, and some would rub off onto dryer surfaces during handling.

Fogging may not work in combination with pneumatic systems because the spray would drift into the air ducts and deposit, causing a buildup and caking on the side wall, which might eventually plug them. In addition, the 0.2 mm (0.008 in.) nozzle orifices need to be checked periodically for wear and maintained.

SUMMARY AND CONCLUSIONS

This study evaluated the effectiveness of a high–pressure water fogging system in controlling grain dust emissions. Results showed the following:

- Air movement was generated by both the grain flow and the spray fogging system. Dropping 2.5 m^3 (60 bu) of grain in 50 s displaced about 2.8 m^3/min (100 cfm) of airflow for the given test chamber geometry. The spray–fog treatments induced additional airflow and redirected dust emissions toward one end of the receiving test chamber.

- Spray fogging treatments S1, S2, and S3, which used 7 to 9 nozzles per 0.76 m of width and applied across the top of the test chamber, reduced dust emissions by 75% to 84% for a dusty corn sample and by 64% to 72% for a clean wheat sample, depending on the spray treatment and grain flow. Spray treatment S4, which used 5 nozzles per 0.76 m, was less effective and more variable.

- The direct applications of the spray–fog to the incoming grain stream as it entered the test chamber had a negative affect. Dust generation and emissions increased with this application technique. The control trials and direct application trials (D1) averaged 17.0 and 22.6 g/tonne dust emissions, respectively.

- The spray fogging system generated considerable fog emissions and deposits depending on the spray treatment. The liquid supply and fog emissions were 855 g/min and 32 g/min, respectively, for treatment S1, which used 9 nozzles per 0.76 m. The rate of depositions for S1 ranged from 1.4 to 7.1 mg/cm^2/min, depending on sample location.

Overall, the spray–fog system reduced dust emissions and redirected air movement significantly. However, it also produced significant fog emissions and deposits, offsetting some of the potential dust control benefit. As such, the adoption of such a system in the grain industry would likely be limited to special applications and processes and must meet regulatory limits.

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